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Monitoring Meteorological Parameters With Crowdsourced Air Traffic Control Data

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ABSTRACT

Up-to-date meteorological information about upper air conditions is crucial for accurate weather modeling and forecasting. Existing techniques to sense meteorological parameters in the atmosphere are costly and provide only limited temporal and spatial sensing resolutions. In this paper, we propose crowdsourcing air traffic control data as a new cost-efficient method to achieve a high temporal and spatial resolution, and large coverage. Our solution leverages Secondary Surveillance Radar Mode S and ADS-B transponder signals that are continuously transmitted by aircraft for air traffic control purposes. It builds on signals captured by the OpenSky Network, a global-scale sensor network crowdsourcing 15+ billions of transponder messages per day from aircraft up to an altitude of 13 km. Based on the decoded data, we infer meteorological conditions such as air temperature, wind speed, wind direction and atmospheric pressure. Our evaluation demonstrates that our approach is effective at estimating these parameters with high resolutions along the tracks of more than 50 percent of all aircraft monitored by the OpenSky Network. Our method delivers estimations for temperature with 0.11°C, wind speed with 0.09 m/s, wind direction with 1.00°, and air pressure with 0.10 hPa average deviation, making those measurements suitable for the assimilation in numerical weather models.

KEYWORDS

crowdsourcing, atmosphere, meteorology, air traffic control, sensor network, temperature, wind, pressure

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1 INTRODUCTION

Live monitoring of meteorological conditions is essential for weather modeling and forecasting. Numerical weather prediction models rely on accurate observation data for estimation of air temperature, wind and atmospheric pressure over space and time. For example, the atmospheric weather model developed by the international Consortium for Small-scale Modeling (COSMO)[1], which is used for weather forecasting by the national meteorological services of Germany, Switzerland, Italy, Greece, Poland, Romania, Russia and Israel, relies on various types of surface-level and upper air observations for estimating the atmospheric conditions along a three-dimensional grid space.

Upper air meteorological information is particularly important for such weather models [11]. Obtaining observations about upper air atmospheric conditions is however much more difficult than surface-level measurements which can be obtained with existing ground-based sensor networks (e.g. Weather Underground[2]). The challenge with monitoring upper air atmospheric conditions is that the current measurement techniques do not scale well and therefore lack of temporal and spatial resolution [4, 8]. For example weather balloons equipped with meteorological sensors, still one of the major source of information for weather models, are expensive to launch on a regular basis and can only provide sporadic snapshots along the tracks of the balloons. Weather radars require a costly infrastructure on the ground and only provide data directly above the radars.

Aircraft have the potential to provide a scalable solution in this context. According to Flightradar24[3], more than 10'000 aircraft are airborne across the globe at any point in time, and the tendency is increasing. Harvesting meteorological information from these aircraft therefore constitutes an exceptional sensing opportunity for meteorology. For this reason, several efforts are considering the use of aircraft for meteorological monitoring. The Aircraft Meteorological Data Relay (AMDAR) [24] and the meteorological routine air report (MRAR) [22] programs have centered on building out an infrastructure to collect and disseminate meteorological data from aircraft. However, these solutions require aircraft to upgrade their communication systems or install new systems, an endeavor that is very costly and slow in the aviation domain. There is little

[1] http://www.cosmo-model.org
[2] https://www.wunderground.com/
[3] https://www.flightradar24.com/

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incentive for many of the aircraft owners to invest money into such an infrastructure since the data is often not providing a direct value to the aircraft owners themselves. As a consequence, only very few aircraft exist today which support these systems and it is very unlikely that the situation will change in the future. An alternative approach proposed in [14] suggests combining information from publicly available flight tracking data sites. This approach requires no special instrumentation but the information from these sites is limited and allows only the estimation of the wind which is not sufficient for accurate weather modeling.

In this work, we address the question if it is possible to leverage aircraft as a large-scale and flexible sensor network for estimating various meteorological parameters including *temperature*, *pressure* and *wind*, but without the need for special instrumentation on the aircraft. Existing sensors on the aircraft measure different parameters of the atmosphere and send derived data in ATC messages. This communication consists mainly of periodic ADS-B messages and responses to interrogations from secondary surveillance radars (SSR). Aircraft transmit both types of messages on the 1090 MHz Mode S channel. De Haan et al. [9] showed that the assimilation of weather data derived from Air Traffic Control (ATC) messages collected by a single radar has a positive effect on the quality of the forecasts. In the work of De Haan et al., the ATC messages were provided directly by ATC. We consider it unlikely that ATC institutions share radar data for meteorological parameter estimation on a large-scale in the near future since ATC radars are operated by individual countries and represent a safety-critical infrastructure. In contrast, we propose to use receivers operated by the crowd to passively receive and collect ATC messages. Such data is already collected at scale today by crowdsourcing-based ground sensor networks such as the OpenSky Network [18] and made available through online databases and APIs. A solution that is based on such crowdsourced air traffic control data would therefore fulfill the need for upper air observation data without requiring additional equipment on the aircraft.

In order to realize the proposed approach, a series of challenges have to be addressed. First, determining the sender of SSR responses and its location is error prone because the aircraft address is combined with the message checksum. Second, the message type of SSR responses is not specified explicitly and we need to infer the required data using probabilistic techniques. Finally, the data we receive from crowdsourced receivers is noisy and we need to remove outliers. We therefore need to develop robust techniques for fusing and correlating the data from multiple sensors in order to estimate the meteorological parameters.

Our results indicate that using crowdsourced air traffic control data, it is possible to ultimately estimate temperature with 0.11°C, wind speed with 0.09 m/s, wind direction with 1.00°, and air pressure with 0.10 hPa average deviation when compared to radiosonde reference data. Our developed methods further provide meteorological observations for more than 50% of existing aircraft while less than 1 percent of the observed aircraft currently support AMDAR and MRAR. Our approach therefore provides a unique opportunity to obtain a large number of meteorological observations from aircraft for assimilation in numerical weather models.
The main contributions of this paper are the following:

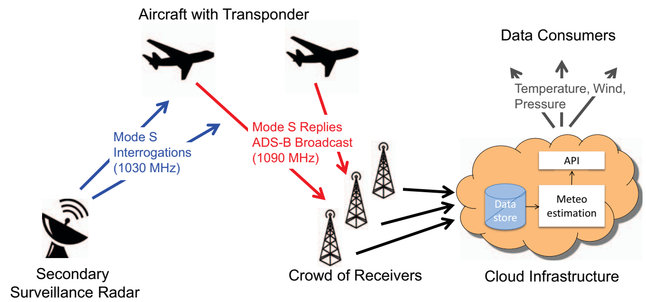


Figure 1: System architecture.

- We propose to use crowdsourced air traffic control data to infer the meteorological parameters such as temperature, pressure and wind.
- We develop a decoder which is able to deduce all required information contained in aircraft transponder SSR replies without the knowledge of the corresponding SSR interrogations by fusing messages of different receiver locations. This enables to obtain meteorological data on a large-scale from passively collected aircraft messages.
- We evaluate the accuracy of using crowdsourced air traffic control data for meteorological parameter estimation and compare the obtained results with data from weather balloons, a numerical weather model used by national meteorological services, and AMDAR.
- We evaluate the availability of the required data (and thus the coverage of our approach) for meteorological parameter estimation at different locations worldwide and demonstrate that our approach is able to provide meteorological observations for more than 50 percent of the aircraft.

2 USING AIR TRAFFIC CONTROL DATA

In this section, we discuss the system to obtain crowdsourced air traffic control data and the methods to infer meteorological data.

2.1 Air Traffic Control Background

We propose a meteorological monitoring system based on data from legacy air traffic control communications such as secondary surveillance radar (SSR) and the newer automatic dependent surveillance – broadcast (ADS-B) systems. Aircraft flying according to instrumental flight rules are required to support SSR and more than 70 percent of the existing aircraft already support ADS-B [19]. To support both types of surveillance technologies, aircraft are equipped with an onboard Mode S transponder. In SSR, the transponder listens to interrogations by ground radars and other aircraft in vicinity and respond to these interrogations with short messages including information such as altitude, velocity and orientation of the aircraft. In ADS-B, aircraft periodically transmit messages to indicate their position, altitude and velocity without being interrogated.

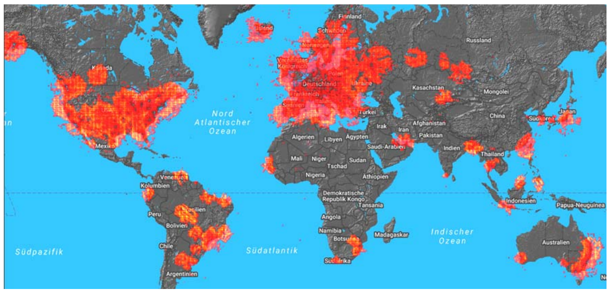


Figure 2: Reception range of SSR Mode S and ADS-B messages with 800+ crowdsourced receivers.

	Required values	Source	
		SSR Mode S	**ADS-B**
Temperature	Mach number	BDS 60	–
	True airspeed	BDS 50	–
Wind	Mag. heading	BDS 60*	–
	True airspeed	BDS 50	–
	True track angle	BDS 50	Velocity msg
	Ground speed	BDS 50	Velocity msg
Pressure	Pressure altitude	Altitude code	Position + velocity msg
Position	GPS altitude	–	Position + velocity msg
	GPS coordinates	–	Position msg

* Only the magnetic heading which first needs to be converted to the true heading is available.

Table 1: Sources for the estimation of meteorological parameters by using air traffic control messages.

2.2 System Overview

We propose a meteorological monitoring system based on air traffic control receivers that collect SSR and ADS-B messages and forward the collected data to a cloud infrastructure for meteorological parameter estimation, fusion, and distribution. Our system architecture is depicted in Figure 1. In this work, we leverage the OpenSky Network [18] for data collection of SSR and ADS-B messages. The OpenSky Network is a crowdsourcing initiative to collect air traffic control data and making the collected data available to third parties. The OpenSky receivers are typically low-cost software radios such as RTL-SDR USB dongles that are attached to a computer or a Raspberry Pi and are operated by volunteers at Universities or at people's homes.

As of this writing, the OpenSky network collects around 15 billion messages per day from more than 800 online receivers deployed around the world. The actual worldwide reception coverage is depicted in Figure 2. Currently, Europe and the USA are almost entirely covered, while other regions in the world have partial coverage. The coverage in all regions is constantly growing, yet a single sensor can receive transponder signals up to a distance of 700 km, allowing theoretically to cover the whole world with a few thousand contributing sensors.

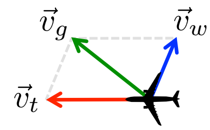


Figure 3: Vector relation for wind estimation.

2.3 Meteorological Parameter Estimation

The goal of our system is to estimate the temperature, pressure and wind from the ADS-B and the SSR Mode S roll-call replies[4] that the aircraft transmit and that we collect through the OpenSky Network. We generate individual meteorological observations by combining information from different SSR Mode S and ADS-B messages. Table 1 gives an overview of the ADS-B and SSR Mode S message types which can be used to estimate the different meteorological parameters. We refer to the standards [13, 16, 17] for the exact definition of the message types. For the estimation of some parameters, we could make use of different messages because ADS-B and SSR Mode S replies often provide redundant information. In such cases, we tend to prioritize ADS-B messages because the decoding includes no uncertainties as we will see later, and ADS-B is also broadcast in the absence of interrogators (e.g. non-radar areas). To assign a position to an observation, we rely exclusively on the aircraft position as advertised in ADS-B position messages.

Currently, not all aircraft are equipped with ADS-B enabled transponders. A mandate for this technology will become effective by 2020. But even after 2020 the decoding of SSR Mode S will still be necessary. As indicated by Table 1, the estimation of temperature, wind speed, and wind direction requires SSR Mode S messages since necessary information is only contained in SSR Mode S messages.

2.3.1 Temperature Estimation. We derive the temperature from the true airspeed (BDS 50) and the Mach number (BDS 60) in SSR Mode S replies as indicated in [4–6, 8]. The Mach number M is the ratio of the true airspeed v_t and the speed of sound c in the air $M = \frac{v_t}{c}$. The speed of sound is not constant but depends primarily on the temperature. Actually, the speed of sound also depends on the humidity and other factors but their influence is much smaller. Thus, the relation between temperature, true airspeed and Mach number can be approximated by $T = \kappa \cdot \frac{v_t^2}{M^2}$. The true airspeed is denoted by v_t in m/s and M is the dimensionless Mach number. The temperature is given in Kelvin. The factor κ is assumed to be constant and is given by $\kappa = \frac{m}{\gamma R}$. Where $\gamma = c_p/c_v = 1.397774$ is the ratio of specific heats, $R = 8.3145\,\text{J/mol}$ is the molar gas constant and $m = 0.0289645\,\text{kg/mol}$ is the molar mass of dry air.

2.3.2 Wind Estimation. The method we use to derive wind estimations is analogous to the derivation in related work [4–6, 8, 14]. The movement of an aircraft is not only determined by the position of the control surfaces and the thrust of the engines but also by the drift that is caused by wind. The relation of the different vectors is depicted in Figure 3. The wind vector can therefore be derived using the vector subtraction $\vec{v}_w = \vec{v}_g - \vec{v}_t$. The vector $\vec{v}_t$ is defined by the velocity relative to the air (true airspeed, BDS 50 of SSR Mode S

[4]In the rest of the this paper, we simply refer to Mode S replies for these messages

replies) and by the direction in which the nose of the aircraft points (mag. heading, BDS 60 in SSR Mode S replies). The vector $\vec{v}_g$ is defined by the velocity relative to the ground (ground speed, BDS 50 in SSR Mode S replies) and by the direction of the ground track of the aircraft (track angle, BDS 50 in SSR Mode S replies). The wind speed corresponds to the length of the wind vector $\|v_w\|$ and the wind direction is given by the direction of the wind vector $\angle v_w$. In meteorology, the wind direction is the direction from which the wind blows. This means the wind direction is opposite to the direction of the wind vector. For this reason, we shift the direction of the wind vector by 180 ° to obtain the wind direction.

2.3.3 Pressure Estimation. Aircraft usually determine their altitude using a barometer. The altitude derived by these means is called *pressure altitude*. The following relation and the values defined by the International Standard Atmosphere (ISA) are used to convert the pressure measurement P into the corresponding altitude value h [15, 24]:

$$h = \frac{T_0}{L}\left(\left(\frac{P}{P_0}\right)^{-LR/g} - 1\right)$$

In reality the reference pressure P_0 is location and weather dependent. This means that the calculated altitude differs from the true altitude. Since it is impractical to keep it up-to-date, P_0 is constantly set to 1013.25 hPa (except for very low altitudes). Vertical separation between different aircraft is still guaranteed because all aircraft in the same area experience the same deviation of altitude. In order to estimate the measured pressure, we reverse the pressure altitude calculation. For this we use the above relation and the constant values defined by the ISA.

3 DATA PROCESSING

Relying on crowdsourced information introduces many data processing challenges for the decoding and parameter estimation. For example, low-cost crowdsourced receivers tend to provide a significant number of erroneous messages or are not able to capture all the messages sent by the aircraft. Furthermore, the transponders of different aircraft tend to behave differently and fusing the information from different aircraft must therefore take these differences into consideration. This section describes how we addressed these challenges in order to make the crowdsourced data from the OpenSky Network suitable for meteorological parameter estimation.

3.1 Message Decoding

The ADS-B and SSR Mode S reply messages we receive from the OpenSky Network are in raw format (messages as bit strings in binary format) and the first step in our processing pipeline is to decode these messages. Decoding ADS-B messages is simple because ADS-B is a broadcast protocol and the receivers can identify the emitting aircraft and message type from the message headers. However, for many message types in SSR Mode S, and in particular for Comm-B registers which are needed in our work, there is no type information in the header and the aircraft address is not given explicitly (the aircraft address is XORed with a checksum). This poses a challenge in our processing pipeline, because unlike radars which know what content to expect in SSR Mode S replies based on their own interrogations, OpenSky only receives the SSR Mode S replies from the aircraft and does not provide any information about the interrogations.

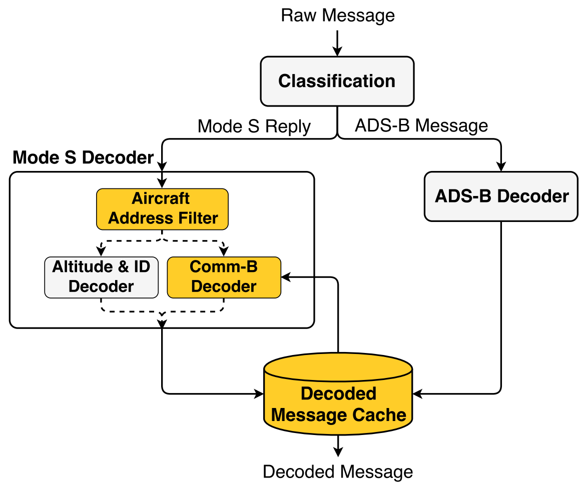


Figure 4: Overview of the SSR Mode S and ADS-B message decoder architecture.

In principle, it is possible to receive the SSR Mode S interrogations, but these interrogations are sent on a separate uplink frequency (1030 MHz) using a larger signal bandwidth than the downlink on 1090 MHz and none of the deployed OpenSky receivers are able to receive such signals. Even if the receivers would be equipped with necessary hardware to receive the uplink, the receivers would still need a line-of-sight connection to the radars to successfully capture interrogations. This is generally not the case since both the radars and the crowdsourced sensors are located on the ground. In addition, secondary radars rely on rotating directional antennas with beams pointed towards the sky. This means that the receivers would only have poor reception when the antenna is not oriented towards them. All the mentioned challenges make the approach of collecting the interrogations on a large-scale much less practical compared to only collecting the replies.

To address this challenge, we propose a probabilistic decoder that manages to identify aircraft (transponder) address and message type (BDS register type) in Mode S replies without the corresponding radar interrogations. An overview of the proposed probabilistic decoder is shown in Figure 4. Incoming transponder messages are first classified as ADS-B or SSR Mode S reply. For this part, we rely on the downlink format (DF) messages field which is available in all transponder messages. ADS-B messages are decoded in a classical way based on the aircraft address and message type included in each message. In contrast, SSR Mode S replies are first passed through an aircraft *address filter* which relies on the history of previously received SSR Mode S messages. SSR Mode S reply messages that pass the address filter are then processed by the *Comm B decoder* which performs structural analysis of the received messages in combination with consistency checks from information based on the history of previously received SSR Mode S and ADS-B messages in order to classify the message type based on a probabilistic model.

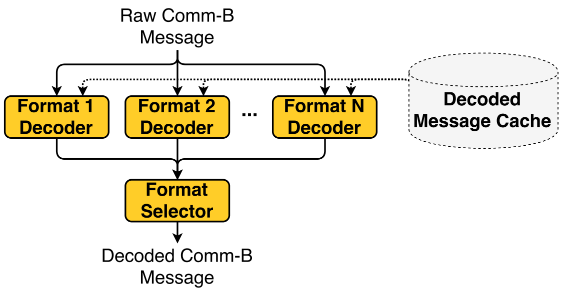


Figure 5: Overview of the Comm-B message decoder.

The address filter and Comm B decoder blocks are described in more details in the following.

3.1.1 Address Filter. To link a received message to an aircraft, we need to extract the aircraft address from a data field that contains the address XOR-ed with the parity of the message. Under the assumption that the message did not suffer from bit errors, we can extract the aircraft address from the parity by XOR-ing the parity with the CRC of the received message body. Of course, with this approach the parity can no longer be used to check the integrity of the message. Since the 1090 MHz channel over which the SSR Mode S replies are transmitted is highly overloaded, and in practice, many bit errors occur [23], we need however to ensure the integrity of the message because messages with bit errors would otherwise result in faulty aircraft addresses.

We propose and evaluate two different filtering strategies to correctly decode the aircraft address of the aircraft and to discard corrupted messages in the presence of bit errors. Both filters build on previous messages to infer the aircraft address which could potentially be in the coverage of the receiver.

Seen-before filter: With the seen-before filter, we count the number of times an aircraft address has been seen before in SSR Mode S replies (i.e. extracted from the parity) and store this information in a cache. The message itself is stored in a message queue. We remove a message from the queue and forward it to the Comm-B decoder only if the aircraft address has been seen more than n times. The threshold n defines the responsiveness of the filter and the likelihood that an address is decoded. Old aircraft addresses are evicted from the address cache after 10 minutes, corresponding approximately to the time it takes for an aircraft to pass the reception range of a receiver.

All-call filter: This filter exploits the nature of so called all-call replies. These messages are used by the interrogators (radars) to discover new aircraft which entered their operational range. The all-call replies include the aircraft address separate from the CRC. Instead the CRC is combined with the interrogator address. There is only a small number of valid interrogator IDs (80 IDs) compared to the number of possible aircraft addresses (2^{24}). Therefore, the probability that the message is corrupted if a valid interrogator address is included in the message is small: $80/2^{24} = 0.000477\%$. Similar to the seen-before filter, all aircraft addresses from messages with valid interrogator addresses are stored in a cache. The replies are only forwarded to the Comm-B decoder if the aircraft address of the message is contained in the address cache. Again, old aircraft addresses are evicted from the address cache after 10 minutes.

3.1.2 Comm-B Message Decoder. The received SSR Mode S reply messages can now be assigned to an aircraft based on the aircraft address but the type of the message (i.e., the BDS register) is still unknown. The Comm-B message decoder (depicted in Figure 5) therefore first guesses the Comm-B field of the SSR Mode S reply based on a combination of structural tests and consistency checks. From the message specification, we know that there are certain bit combinations which are not valid for a given format type. For example, if the status bit of a parameter indicates that the corresponding field is invalid, the field bits must be set to zero. If a single inconsistent bit is detected in a structure check, we do no longer consider the corresponding message format for the message. With the bit combinations, we do not require every field of the BDS register to be filled since according to the standard [16], not all fields must be populated with data.

In a second step, we apply consistency checks to the decoded messages with the remaining formats. For this, we define a set of checks which compare two similar parameters from messages of the same aircraft within a small time window. We compare parameters from the same message, from previously decoded messages of the same type but also from messages of other types. We also use data from ADS-B messages for comparison. As an example, the ground speed contained in a SSR Mode S message can be compared to the ground speed value contained in the ADS-B message. For the comparisons that require previously decoded messages, we rely on a decoded message cache.

From the applied consistency checks, we get a confidence for each message type. Based on this confidence, our decoder selects the message format with the highest confidence. If none of the decoded message formats exhibits a large enough confidence value, no message format is chosen and we drop the message. This can for example happen if messages contain bit errors or if there is an ambiguity between multiple message types due to the content of the message being plausible for different BDS registers.

3.2 Handling Decoding Errors and Noise

After message decoding, we fuse the data from the different receivers and estimate the temperature, the wind speed, the wind direction and the pressure along the tracks of the aircraft.

3.2.1 Outlier Filtering. We apply outlier filtering before smoothing the data, as the error of a single outlier may otherwise pollute the neighboring data points. This means that the data still exhibits quantization. In addition, a perfectly valid signal may not change over many successive sampling points. These facts make it difficult to find suitable parameters to filter outliers with standard approaches, such as Thompson Tau or Median Absolute Deviation outlier filtering. Even the change of one quantization step will always be treated as an outlier if the rest of the window consists of nothing but exactly equivalent values.

To deal with these problems, we apply the following method. For every value, we know the quantization step size. We assume that the values do not vary rapidly and that the maximum possible change is proportional to the quantization step size. For a single parameter of a single aircraft we apply sliding window filtering over time. For every position of the window, we examine if the center point of the window is an outlier or not. For this, we calculate the median of the remaining points in the window and calculate the difference of this median and the value of the center point. Only if this difference is larger than n times the quantization step, we consider the center value as an outlier. We call n the outlier filter *factor*. For angular values we can not use the median, instead we use the circular mean for the comparison. Since most of the outliers are caused by the Comm-B decoder selecting a wrong message format, it is very likely that the other fields included in the same message are wrong as well. Therefore, the outlier filter discards the whole message that contains the detected outlier.

Analogous to classical methods such as Aircraft Meteorological Data Relay (AMDAR) [24] and MRAR [22], we discard measurements that are obtained when the aircraft exhibits a large roll angle. A large roll angle indicates that the aircraft is turning and the sensors of an aircraft can produce bad values during aircraft maneuvers due to irregular air flows around the sensors.

3.2.2 Mitigating Quantization Noise. In order to mitigate quantization noise, we apply a smoothing filter after the outlier filtering. Common filters for this purpose are low or band pass filters. However, such filters are not well suited for the kind of data we obtain from the decoder. The data is sampled at irregular intervals and such filters assume equidistant sampled signals. Instead, we apply sliding window filtering to single parameters of a single aircraft over time and focus on the center point. A new value for the center point is determined by first calculating a linear regression using all points in the window and then calculating the value of this regression line at the position of the center of the window. This does not work for circular data like heading angles. Therefore, we use the circular mean for angles.

4 EVALUATION METHODOLOGY

This section describes the reference data sets we obtained in order to assess the accuracy of our approach. Ideally, we would want to assess the accuracy of our method by comparing the obtained meteorological parameters with a ground truth. However, obtaining such a ground truth happens to be a great challenge because reference measurements obtained with other methodologies also exhibit measurement errors. In addition, these reference measurements may not happen at the exact same location and time which also introduces a bias in the comparison. Nevertheless, we compare our results to three independent reference datasets in order to better understand the estimation accuracy.

4.1 Reference Data Sets

Radiosonde: The first dataset consists of reference data from radiosondes operated by the Federal Office of Meteorology and Climatology of Switzerland (MeteoSwiss), the national meteorological agency in Switzerland. A radiosonde consists of measurement equipment which is attached to a gas-filled balloon. During the ascent, the radiosonde provides a vertical profile of the atmosphere up to approximately 30 km altitude. The radiosondes of MeteoSwiss are launched twice a day approximately 1 hour before the synoptic hour (00 UTC and 12 UTC). The launch location is Payerne, Switzerland. The measurement data of the radiosonde includes temperature, wind speed, wind direction, pressure, dew point as well as accurate timestamps and GPS position. The temporal resolution of the measurement points is usually 1 second which leads to approximately 5 meters resolution vertically. According to MeteoSwiss the uncertainty at 2 km altitude is 0.1 K for the temperature, 0.2 m/s for the wind speed, 2% for the relative humidity and 0.2% for the pressure. Radiosonde reference data happens to be relatively accurate but the data points obtained with this method are quite far apart from the aircraft since they cannot fly at the same time in the same airspace.

COSMO: The second dataset is reference data from the numerical weather prediction model of MeteoSwiss. We refer to this data source as COSMO. This weather model mainly covers Switzerland and the border region. Vertically the data about the atmosphere is available from ground up to 12 kilometers altitude. The altitude of the height levels are not constant for the whole model area but they depend on the topography of the terrain. The weather model has an horizontal resolution of approximately 1 kilometer and a vertical resolution from about 20 meters on ground up to 500 meters at 12 kilometer altitude. The weather model is assimilated with data from ground-based weather stations, radar data, radio soundings from different locations, wind profiler data and AMDAR observations. The numerical weather model is calculated every 3 hours and produces forecasts covering the next 33 hours with a granularity of 1 hour. For this work, only the temporally non-overlapping forecasts with smallest time difference to the considered time are used.

AMDAR: The third reference dataset consists of AMDAR observations that aircraft sent out on the aircraft communications addressing and reporting system (ACARS) over very high frequency (VHF) radios. AMDAR is a system which is dedicated to collect meteorological measurements. Only very few aircraft transmit AMDAR information and this dataset is therefore relatively small. Between 5/27/2016 and 1/22/2017, the AMDAR data set contains 366 *Enroute Weather Reports* which contain a total of 774 measurements. Most measurements are taken at high altitudes between 8 km and 12 km. AMDAR data is extracted and preprocessed (averaged) on the aircraft. We only consider data points from aircraft for which our method provides also observation points. AMDAR measurements tend to have worse quality compared to radiosonde measurements [4], however since the measurements originate from the same aircraft as for our method, the distance between the observations from the both methods is smaller than radiosonde data.

4.2 Collocations

In order to compare the estimated meteorological data points to the reference data sets, we look for collocated measurement points. Since the measurements from the different data sets do not match exactly the derived estimations in terms of location and time, we have to tolerate a distance in the collocations. The distance between two data points is defined by the horizontal and the vertical distance as well as by the time difference. When selecting collocations, we prioritize small vertical distances for larger horizontal distance and time offsets since the altitude has the strongest influence on most meteorological parameters. The distributions of the vertical, horizontal distance and time offset of collocations when using the

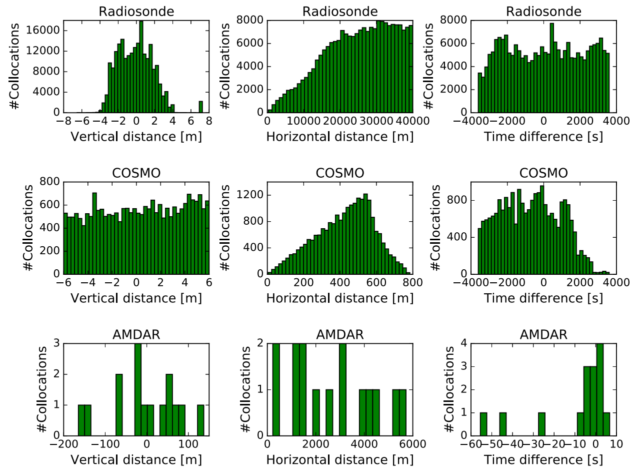


Figure 6: Distribution of the collocation metrics when using the radiosonde (top row), COSMO weather model (middle row) or AMDAR (bottom row) reference data.

radiosonde (top row), COSMO (middle row) or AMDAR (bottom row) reference data is shown in Figure 6.

Before collocating the estimated data with reference data, we filter the estimated meteorological parameters since the reference data (COSMO and AMDAR) is based on averages as well. For this, we use a sliding window and consider the point in the middle. We remove outlier points if the difference to the mean of the rest of the points is larger than two times the standard deviation of the rest of the points (window size of 45 s). Furthermore, we replace the middle point with the mean of the remaining points in the window (window size of 20 s).

As comparison metric, we consider the root-mean-square deviation (RMSD). This nomenclature takes into account that our ground truth does not originate from the same place both spatially and temporal as our estimated data. In addition, the reference data are also merely estimations experiencing their own errors. Therefore, the RMSD should be regarded as an upper bound on the estimation error, while the true error of our estimators is expected to be smaller.

In order to visualize many parameter difference values, we make use of box plots. In box plots, the box extends from the lower to the upper quartile values of the data and the line represents the median. The whiskers reach $1.5 \cdot \mathrm{IQR}$ past the first and third quartile, with IQR being the interquartile range. This means that the box represents 50% of the data, while the whiskers together with the box span 99.3% of the data.

5 EVALUATION

Our evaluation consists of three parts. In the first part, we evaluate the performance of our decoder. In the second part, we evaluate the accuracy of the meteorological parameters derived by our approach compared to the reference data sets. Finally, we analyze the coverage of our method at eight different sites around the world.

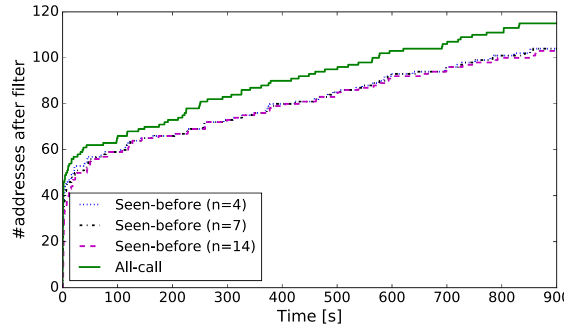


Figure 7: Seen-before filter output for messages received in Thun, Switzerland.

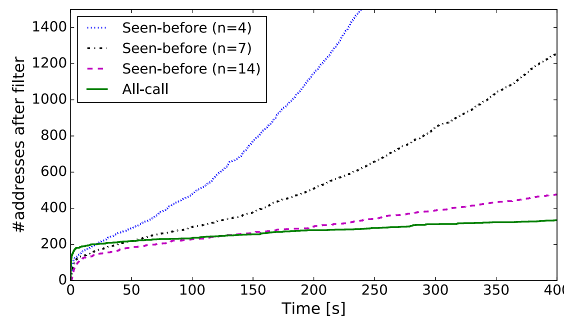


Figure 8: Seen-before filter output for messages received near the airport of Frankfurt (first 400 seconds).

5.1 Decoder Performance

5.1.1 Address Filter. To evaluate the performance of the filters of our probabilistic decoding scheme, we consider the filtered output from two different receivers. One receiver in Frankfurt, Germany, is located close to a large airport and the other receiver in Thun, Switzerland, is far away from any large airport. The duration of the Mode S recording is 15 minutes for both receivers.

The results for different n for the receiver in Thun are very similar (Figure 7). Surprisingly, the opposite is the case for the receiver in Frankfurt (Figure 8). The large difference in slope of the different seen-before settings suggests that we decode a lot of invalid aircraft addresses that show up only very few times. This suggests that the noise level from different sensors highly depends on the receiver setup and the radio environment. Most of the aircraft seem to be within the operational ranges of multiple interrogator and therefore send all-call replies to multiple interrogators. Only 2.44% of all interarrival times are larger than 1 second. Additional analyses also indicate that a single transponder often sends 3–5 replies to the same interrogator in a very short time, or, that the same reply is received multiple times by the receiver (e.g. due to multipath effects).

For the rest of the evaluations in this work, we use the all-call filter since it performs better in an environment with corrupted messages and it performs similar in an environment with almost no corrupted messages.

5.1.2 Decoding Performance. We evaluate our probabilistic decoding scheme by decoding the same set of transponder messages

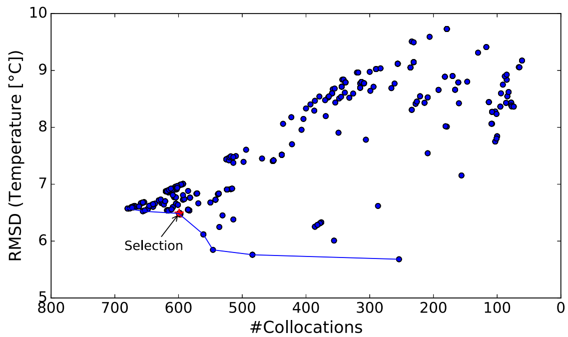


Figure 9: Pareto plot with the Pareto frontier of the Comm-B decoder evaluation.

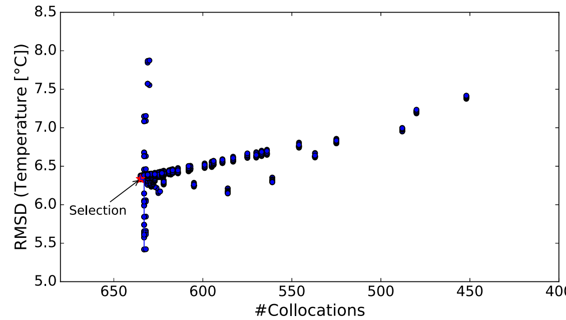


Figure 10: Pareto plot of temperature estimations when varying all three parameters of the filtering.

with different decoder configurations. The SSR Mode S and ADS-B data stem from a receiver located in Thun, Switzerland. The distance between the radiosonde launch location and the receiver is approximately 55 km. The duration of the data recording is 10 minutes. Three main parameters of the Comm-B decoder are varied for the evaluation. The consistency source defines which type of information is used in the plausibility checks. The consistency level determines the tightness of the limits for the plausibility checks. Finally the minimum confidence level defines the amount of plausibility checks that must be successful in order to accept a decoded message format. We defined a set of consistency source combinations that are compatible with each other.

For every decoder configuration, we obtain a set of decoded SSR Mode S messages which is used to estimate meteorological parameters. The estimated parameters are then evaluated by comparing them to reference data from the radiosonde sounding in Payerne, Switzerland. Thus, for every decoder configuration, we obtain the number of collocations and the RMSD.

The goal of the evaluation is to maximize the number of collocations (which is proportional to the number of decoded messages) and at the same time to minimize the RMSD. In order to select an optimal decoder configuration, we plot the obtained results in a Pareto diagram which is depicted in Figure 9. Each point in this plot represents one decoder configuration. We chose to analyze the temperature parameter since the variation of this meteorological measurement is the smallest and the estimation requires two important SSR Mode S BDS registers, BDS 50 and BDS 60.

In summary, simpler consistency checks produce better results. We chose a configuration in the Pareto frontier (depicted as a line) for which many combinations in the vicinity produce good results as well. For our selected configuration, the Comm-B decoder uses the values in the same message and values in previously decoded Comm-B messages of other message types. The consistency level of our selection is 4 out of 4. This corresponds to consistency checks with tight limits. The minimum confidence setting of our selection is 0.5 which means that 50% of the consistency checks applied to a message must be successful. For all other evaluations in this work we use this configuration for the Comm-B decoder.

5.2 Meteorological Parameters

5.2.1 Noise Mitigation Parameters. In order to reduce the error induced by outliers and quantization, we first start with optimizing the parameters for the outlier filters and quantization noise mitigation techniques used in our implementation. Analogously to the parameter optimization for the decoder, we apply the filters with varying configuration to the same set of decoded messages. For the decoding, we use the optimal configuration determined in the previous section and the same 10 minutes recording of Mode S and ADS-B data.

For the window size of the outlier filter and the smoothing filter we use the values {1, 2, 5, 10, 15, 20, 25, 30, 40, 50, 60} seconds. For the outlier filter factor we use the values {2, 5, 8, 10, 15, 20}. We form the Cartesian product of all values and all inputs in order to determine all evaluated filter configurations. The filtered data is used to estimate meteorological parameters which are then evaluated using reference data from the radiosonde in Payerne, Switzerland. The configuration of the estimation and evaluation is kept constant for all filter settings. For every filter configuration, we determine the number of obtained collocations and the RMSD. In order to select an optimal filter configuration, we plot the obtained points in a Pareto diagram depicted in Figure 10.

We select a Pareto optimal point in the Pareto frontier for which many combinations in the vicinity produce good results as well. The configuration of the selected Pareto optimal point correspond to a window size of 10 seconds and a filter factor of 20 for the outlier filter. The selected Pareto optimal point also corresponds to a smoothing filter window size of 15 seconds. The evaluation for other meteorological parameters yields similar optimal configurations.

5.2.2 Comparison to Radiosonde Reference Data. In this section, we compare a larger set of estimated meteorological data to reference data from radiosonde soundings. The SSR Mode S and ADS-B channel data stem from 4 receivers located around the radiosonde launch location in Payerne, Switzerland, with a maximal distance of 60 km. The data spans a time of 2 hours around the time of the radiosonde sounding at 12 UTC of 13 successive days in June 2016. For the evaluation, we use the optimal configuration determined in the previous sections for the decoder and the noise mitigation.

Figure 11 and Table 2 show the results of the evaluation with radiosonde reference data. The corresponding distributions of the collocation metrics are depicted in Figure 6. The temperature and

Ref. data	Parameter	Estimated data		RMSD	Parameter diff.		Units
		#AC	#Collocations		Mean	Std.dev.	
Radiosonde	Temperature	700	212625	1.640	-0.114	1.636	°C
	Wind speed	700	212223	4.136	0.090	4.135	m/s
	Wind direction	700	212223	40.696	-0.999	40.684	°
	Pressure	726	169042	4.223	0.103	4.222	hPa
COSMO	Temperature	785	22273	2.379	-0.793	2.243	°C
	Wind speed	774	21719	4.412	0.314	4.400	m/s
	Wind direction	774	21719	51.929	4.838	51.703	°
	Pressure	803	19505	3.510	0.504	3.474	hPa
AMDAR	Temperature	8	15	5.983	-2.180	5.572	°C
	Wind speed	8	15	3.651	-0.710	3.581	m/s
	Wind direction	8	15	17.062	-10.075	13.770	°

Table 2: Metrics of the parameters estimated from air traffic control messages when comparing them to radiosonde, COSMO and AMDAR reference data (all altitude bins).

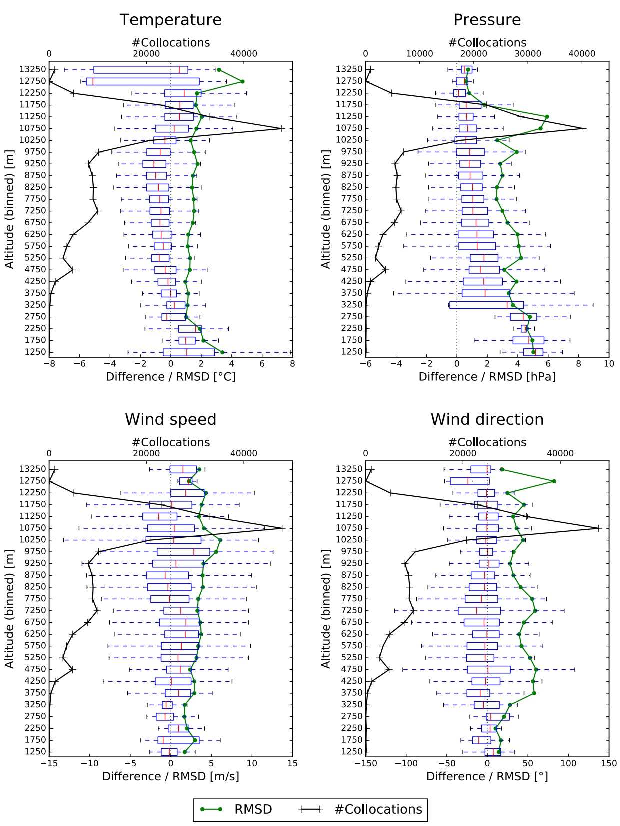


Figure 11: Vertical distribution of the deviation between the parameters estimated from ATC messages and radiosonde reference data.

wind are evaluated with more than 200,000 collocations and the pressure with more than 165,000 collocations. The distribution of the collocations over the altitude is visible in Figure 11. The pressure exhibits a larger positive bias for lower altitudes. In contrast, the error of the wind speed increases with increasing altitude. We investigated if errors are related to particular aircraft models or

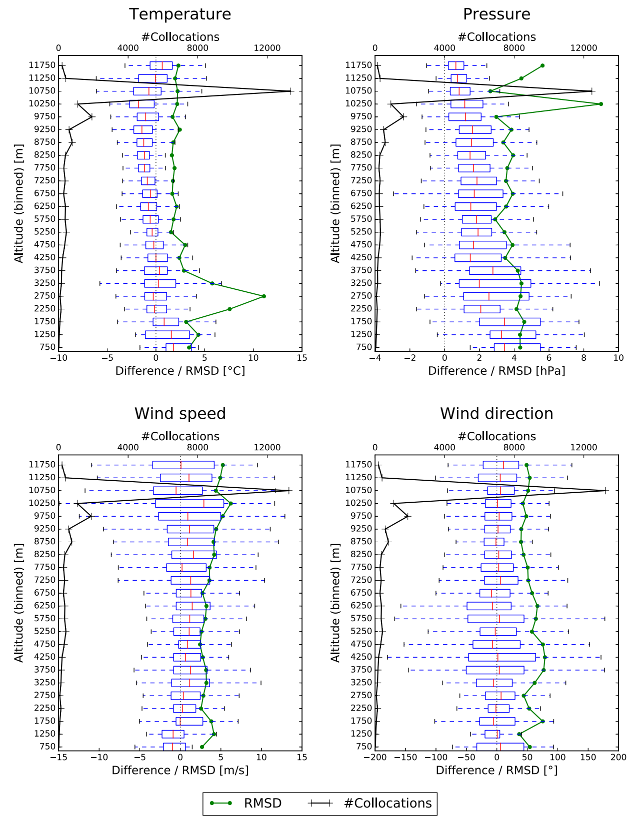


Figure 12: Vertical distribution of the deviation between the parameters estimated from ATC messages and COSMO reference data.

aircraft operators but did not observe any correlation. The deviation of the wind direction has a lot of variation. This is not surprising since the reference data for the wind does show a lot of variation as well.

5.2.3 Comparison to COSMO Reference Data. We evaluate our estimated data by comparing it to the COSMO reference data of eight consecutive days (6/1/2016 until 6/8/2016). We chose a maximum of 6 m for the vertical distance of collocations and use otherwise the same configuration as in the evaluation in Sections 5.1.2 and 5.2.1.

The resulting RMSD, mean and standard deviation values are listed in Table 2. The vertical distributions of the deviation are depicted in Figure 12. The results show that the bias for the temperature, the wind speed and the wind direction is worse. For the pressure the opposite is the case. The evaluation with COSMO data exhibits a larger RMSD at low altitudes. In general, the bias of the different altitude bins follows the bias of the evaluation with radiosonde reference data. We suspect that the main reason for the higher RMSD when using COSMO reference data is the different distribution and availability of the reference data. COSMO reference data is only available at grid points and has a maximum altitude of 12 km, whereas the maximum altitude for the radiosonde data is approximately 30 km and it is available for almost any altitude. Therefore the two methods have a significantly different distribution of the collocation metrics (depicted in Figure 6). Furthermore, the modeling of COSMO can cause deviations that do not correspond to the conditions of the real world.

5.2.4 AMDAR Reference Data. The resulting metrics for the AMDAR reference data are listed in Table 2. Again, we apply limits to match points of the two data sets. This is necessary since the AMDAR measurements are not produced at the exact same time instances as the measurements derived from the air traffic control messages. Furthermore, AMDAR data has a very coarse temporal resolution and air traffic control messages derived measurements are not always available due to lacking coverage or failed decoding of necessary messages. We set the time difference limit to 2 minutes, the vertical distance limit to 200 meters and the horizontal distance limit to 6000 meters. The corresponding distributions of the collocation metrics are depicted in Figure 6. We could only find a small number of collocations (15) due to the small number of AMDAR measurements and due to the limited coverage of the OpenSky sensor network in the beginning of the AMDAR observation period. Furthermore, not every AMDAR aircraft is yet equipped with an ADS-B enabled transponder as the mandate for this technology will only become effective by 2020. Since AMDAR data does not contain the corrected altitude but only contains the pressure altitude, we could not compare the pressure estimations.

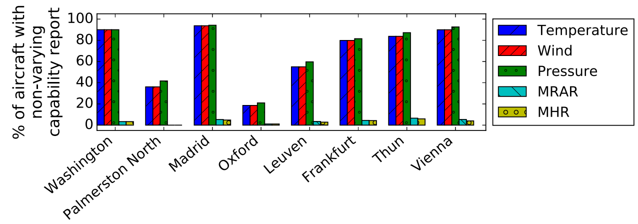
Compared to the RMSD of the evaluation with radiosonde and COSMO, the RMSD of the AMDAR temperature is relatively large (5.98 °C). However, the comparison is biased since the vertical difference of the collocation, the parameter with the most influence on the temperature, is set much higher in the case of AMDAR (200 m instead of 8 m). The RMSD for the wind speed and the wind direction are both better than for the other two reference data sets.

5.3 Density & Availability

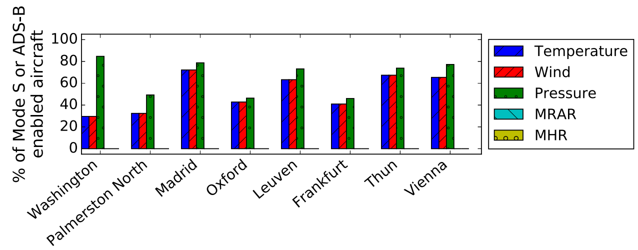
To show how our method improves the number of aircraft that can be used to infer meteorological parameters, we study further the capabilities of existing aircraft and the amount of messages that are available for our passive approach compared to active interrogations by Meteorological Routine Air Report (MRAR) and Meteorological Hazard Report (MHR). MRAR and MHR are both extensions of Mode S to retrieve meteorological parameters from aircraft which require modification and upgrades of the aircraft's equipment.

For the analysis, we rely on SSR Mode S/ADS-B data from eight OpenSky receivers in three continents. For all receivers, a time interval of two hours after 12:00 local time is used. Because not all of the receivers were available at the same time, we chose different days to extract the data. The message rate of the different receivers varies due to the receiver type, the antenna, the obstruction of the line-of-sight path and the location. We use the optimal decoder and filter configurations determined in Sections 5.1.2 and 5.2.1. We do apply outlier filtering, but we do not apply smoothing.

5.3.1 Transponder Equipage & Capabilities. The Mode S capability report (BDS 17) gives an indication of which message types are supported by the aircraft even if they are not interrogated. We



(a) Based on information in capability report messages.



(b) Based on received messages.

Figure 13: Availability of different sources of meteorological information.

analyze the capability reports of aircraft seen by the eight OpenSky sensors. We only consider aircraft with non-varying capability reports, i.e. the majority (> 70%) of the capability reports are identical and for every aircraft we decoded the same capability report at least three times. In order to normalize the number of supporting aircraft across different receivers, we use the total number of aircraft that send non-varying capability reports. Figure 13a depicts the corresponding percentages of aircraft for the eight receiver locations.

The results indicate that the messages which are required in our method to estimate the temperature, wind and pressure are available at every location. There is a tendency that the availability of those messages is higher in the European area compared to the locations on other continents. The exceptions, Washington, Palmerston North and Oxford, might be influenced by the large amount of intercontinental flights.

On average only approximately 4% of all aircraft report to support the meteorological message types MRAR and MHR. This number complies with the numbers stated in related work [22]. However, 67% of the aircraft support the messages that are needed in our method, resulting in a much larger fleet of aircraft for parameter estimation than the classical MRAR and MHR. Despite the ongoing roll-out of MRAR and MHR, we expect this trend to remain valid for many upcoming years.

5.3.2 Interrogated Data. To further understand which messages types supported by the aircraft are actually interrogated, we evaluate the number of received and decoded ADS-B and SSR Mode S messages at the different OpenSky sensor locations. An aircraft is counted for a message type only if the message type has been decoded at least three times. In order to normalize the number of aircraft across different receivers, we use the total number of aircraft for which we decoded SSR Mode S or ADS-B messages. This number gives an indication of how many aircraft are in the air at the receiver location. Figure 13b depicts the corresponding

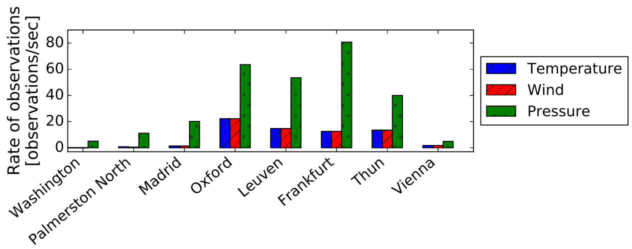


Figure 14: Rate of observations for the different sensor locations.

percentages of aircraft for the eight receiver location. In Figure 14, the corresponding rate of observations are depicted.

The results show that the availability of messages required for temperature, wind and pressure estimation is higher in Europe. Mainly the higher availability of Mode S Enhanced Surveillance (EHS) messages in Europe contributes to this distribution. In North America, the messages required for the pressure estimations are sent by a larger number of aircraft. This indicates that the availability of ADS-B messages is better compared to Europe. According to our result, the meteorological Mode S messages (MRAR and MHR) are transmitted nowhere. In the observed airspace, no interrogator seems to request these message types. In contrast, our method exploits commonly interrogated message types and provides on average meteorological observations for 51% of the aircraft.

6 RELATED WORK

Kapoor et al. presented a method to use machine learning and data from flight tracking websites to obtain wind speed and wind direction information [14]. While our method also allows to derive the wind speed and wind direction, we can further infer other meteorological parameters such as temperature and pressure as required for weather modeling and forecasting, which is not possible with their approach.

De Haan et al. [4–9] and Hrastovec et al. [12] have investigated the use of radar technologies to estimate meteorological parameters of the atmosphere. However in these works, the data is obtained directly from radar sites or from an ADS-C data provider while our approach is to leverage crowdsourced air traffic control data. De Leege [10] et al. investigate techniques to derive meteorological parameters from passive ADS-B measurements only. These techniques have very large mean estimation errors in the range of 9.2 kt and 29.0° for wind, 0.8 hPa for the pressure and 2 K for the temperature which makes them unsuitable for assimilation in weather models. De Haan et al. [7] and Stone et al. [20, 21] suggest passive decoding of Mode S messages. Our work differs by making use of crowdsourced air traffic control data for large-scale meteorological monitoring.

Environmental monitoring, with or without the help of the crowd, has been in the focus for pollution or air quality assessment, e.g. [1–3]. In the contrary, our work focuses on retrieving meteorological parameters of the atmosphere for weather modeling.

7 CONCLUSIONS

We have proposed to use crowdsourced air traffic control data for upper air meteorological monitoring. We have designed, implemented, and evaluated an approach to infer wind speed, wind direction, temperature and air pressure from SSR Mode S and ADS-B messages collected through the OpenSky Network. We show in our evaluation, that our approach allows for estimating meteorological parameters with average deviations to official weather agency data of 0.11°C in temperature, 0.09 m/s in wind speed, 1.00° in wind direction, and 0.10 hPa in air pressure.

In addition, we have evaluated the availability of the required air traffic control data and compared it to other solutions which require infrastructure updates on the aircraft. Our results show that our approach based on crowdsourced data is able to derive meteorological observations for more than 51% of all aircraft while systems such as AMDAR and MRAR provide currently observation data for only less than 1 percent of the aircraft in the considered airspace. Our approach therefore opens new sensing opportunities on a larger scale. In the future, we want to evaluate how weather forecasting models can be improved by assimilating data as derived in this work.

REFERENCES

[1] Oscar Alvear, Carlos T. Calafate, Enrique Hernández, Juan-Carlos Cano, and Pietro Manzoni. 2015. Mobile Pollution Data Sensing Using UAVs. In *Proceedings of the 13th International Conference on Advances in Mobile Computing and Multimedia (MoMM 2015)*. ACM, New York, NY, USA, 393–397. DOI: https://doi.org/10.1145/2837126.2843842

[2] Adrian Arfire, Ali Marjovi, and Alcherio Martinoli. 2016. Mitigating Slow Dynamics of Low-Cost Chemical Sensors for Mobile Air Quality Monitoring Sensor Networks. In *Proceedings of the 2016 International Conference on Embedded Wireless Systems and Networks (EWSN '16)*. Junction Publishing, USA, 159–167. http://dl.acm.org/citation.cfm?id=2893711.2893734

[3] Yun Cheng, Xiucheng Li, Zhijun Li, Shouxu Jiang, Yilong Li, Ji Jia, and Xiaofan Jiang. 2014. AirCloud: A Cloud-based Air-quality Monitoring System for Everyone. In *Proceedings of the 12th ACM Conference on Embedded Network Sensor Systems (SenSys '14)*. ACM, New York, NY, USA, 251–265. DOI: https://doi.org/10.1145/2668332.2668346

[4] Siebren de Haan. 2011. High-resolution wind and temperature observations from aircraft tracked by Mode S air traffic control radar. *Journal of Geophysical Research: Atmospheres* 116, D10 (2011).

[5] Siebren de Haan. 2013. An improved correction method for high quality wind and temperature observations derived from Mode S EHS, Technical Report TR-338. (2013).

[6] S de Haan, LJ Bailey, and JE Können. 2013. Quality assessment of Automatic Dependent Surveillance Contract (ADS-C) wind and temperature observation from commercial aircraft. *Atmos. Meas. Tech* 6 (2013), 199–206.

[7] Siebren de Haan, Marijn de Haij, and Jan Sondij. 2013. The use of a commercial ADS-B receiver to derive upper air wind and temperature observations from Mode S EHS information in the Netherlands, Technical Report TR-336. *Atmospheric Measurement Techniques Discussions* (2013).

[8] Siebren de Haan and Ad Stoffelen. 2009. High resolution temperature and wind observations from commercial aircraft. In *Proceedings of the 8th International Symposium on Tropospheric Profiling.*

[9] Siebren De Haan and Ad Stoffelen. 2012. Assimilation of high-resolution Mode S wind and temperature observations in a regional NWP model for nowcasting applications. *Weather and Forecasting* 27, 4 (2012), 918–937.

[10] A. M. P. de Leege, M. M. van Paassen, and M. Mulder. 2012. Using Automatic Dependent Surveillance-Broadcast for Meteorological Monitoring. *Journal of Aircraft* (2012).

[11] R. J. Graham, S. R. Anderson, and M. J. Bader. 2000. The relative utility of current observation systems to global-scale NWP forecasts. *Quarterly Journal of the Royal Meteorological Society* (2000).

[12] Marko Hrastovec and Franc Solina. 2013. Obtaining meteorological data from aircraft with Mode-S radars. *IEEE Aerospace and Electronic Systems Magazine* (2013).

[13] ICAO 2008. *Technical Provisions for Mode S Services and Extended Squitter.* ICAO. Doc 9871, First Edition.

[14] Ashish Kapoor, Zachary Horvitz, Spencer Laube, and Eric Horvitz. 2014. Airplanes aloft as a sensor network for wind forecasting. In *Proceedings of the 13th international symposium on Information processing in sensor networks*. IEEE Press, 25–34.

[15] Portland State Aerospace Society 2004. *A Quick Derivation relating altitude to air pressure*. Portland State Aerospace Society. Version 1.03, 12/22/2004.

[16] RTCA, Inc. 2011. *Minimum Operational Performance Standards for Air Traffic Control Radar Beacon System / Mode Select (ATCRBS / Mode S) Airborne Equipment*. RTCA, Inc. RTCA/DO-181E.

[17] RTCA, Inc. 2011. *Minimum Operational Performance Standards (MOPS) for 1090 MHz Extended Squitter Automatic Dependent Surveillance – Broadcast (ADS-B) and Traffic Information Services – Broadcast (TIS-B)*. RTCA, Inc. RTCA/DO-260B Corrigendum 1.

[18] M. Schäfer, M. Strohmeier, , V. Lenders, I. Martinovic, and M. Willhelm. 2014. Bringing Up OpenSky: A Large-scale ADS-B Sensor Network for Research. In *ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN)*.

[19] Matthias Schäfer, Martin Strohmeier, Matthew Smith, Markus Fuchs, Rui Pinheiro, Vincent Lenders, and Ivan Martinovic. 2016. OpenSky Report 2016: Facts and Figures on SSR Mode S and ADS-B Usage. IEEE/AIAA Digital Avionics Systems Conference (DASC), Sacramento, CA, USA. (September 2016).

[20] Edmund Keith Stone and Malcolm Kitchen. 2016. Deriving meteorological observations from intercepted Mode-S EHS messages.. In *WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observation (TECO)*.

[21] Edmund Keith Stone and Gary Pearce. 2016. A Network of Mode-S Receivers for Routine Acquisition of Aircraft-Derived Meteorological Data . *AMS Journal of Atmospheric and Oceanic Technology* (2016).

[22] B Strajnar. 2012. Validation of Mode S Meteorological Routine Air Report aircraft observations. *Journal of Geophysical Research: Atmospheres* 117, D23 (2012).

[23] Martin Strohmeier, Matthias Schäfer, Vincent Lenders, and Ivan Martinovic. 2014. Realities and Challenges of NextGen Air Traffic Management: The Case of ADS-B. *IEEE Communications Magazine* (2014).

[24] World Meteorological Organization 2003. *Aircraft Meteorological Data Relay (AMDAR) Reference Manual*. World Meteorological Organization. WMO-No. 958.